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[54] **FILTERING TECHNIQUE BASED ON HIGH-FREQUENCY PLANT MODELING FOR HIGH-GAIN CONTROL**

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[56] **References Cited**

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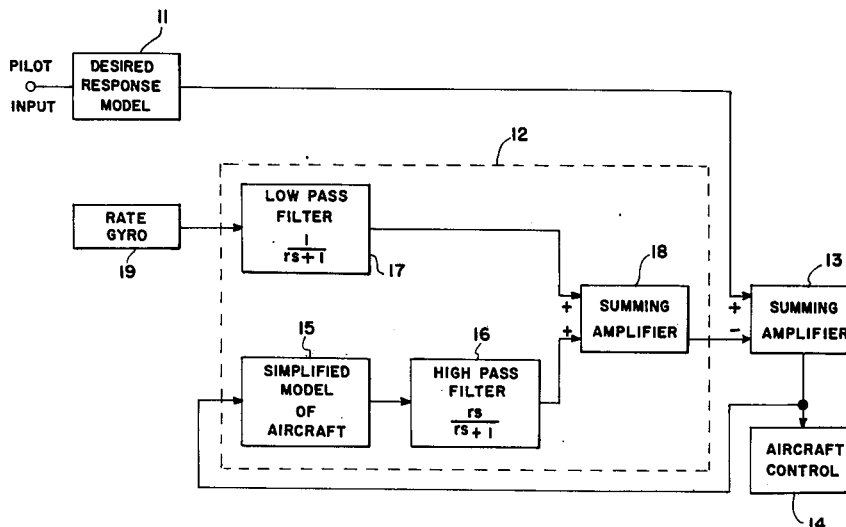*Primary Examiner*—Trygve M. Blix
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[57] **ABSTRACT**

This invention is an improvement in aircraft control systems that utilize feedback motion sensors to generate a control signal to control the aircraft. The improvement consists essentially of a complementary filter comprising a simplified model of the aircraft, a high-pass filter, a low-pass filter and a summing amplifier. The control signal is applied to the simplified model of the aircraft which attempts to compute the vehicle response to the signal. This computed response is then fed into the high-pass filter to eliminate long-term errors in the calculated response, with the result that a good estimate of the high frequency content of the aircraft motion is obtained. In order to obtain a good estimate of the low frequency content of the motion a rate gyro signal is fed through the low-pass filter that eliminates all of the offending noise. The outputs from the high-pass and low-pass filters are summed by the summing amplifier to produce an estimated rate which is then used as a motion feedback signal. The use of the complementary filter permits a substantial increase in frequency band-width due to the simultaneous reduction in noise amplificaton and control limit-cycle tendencies.
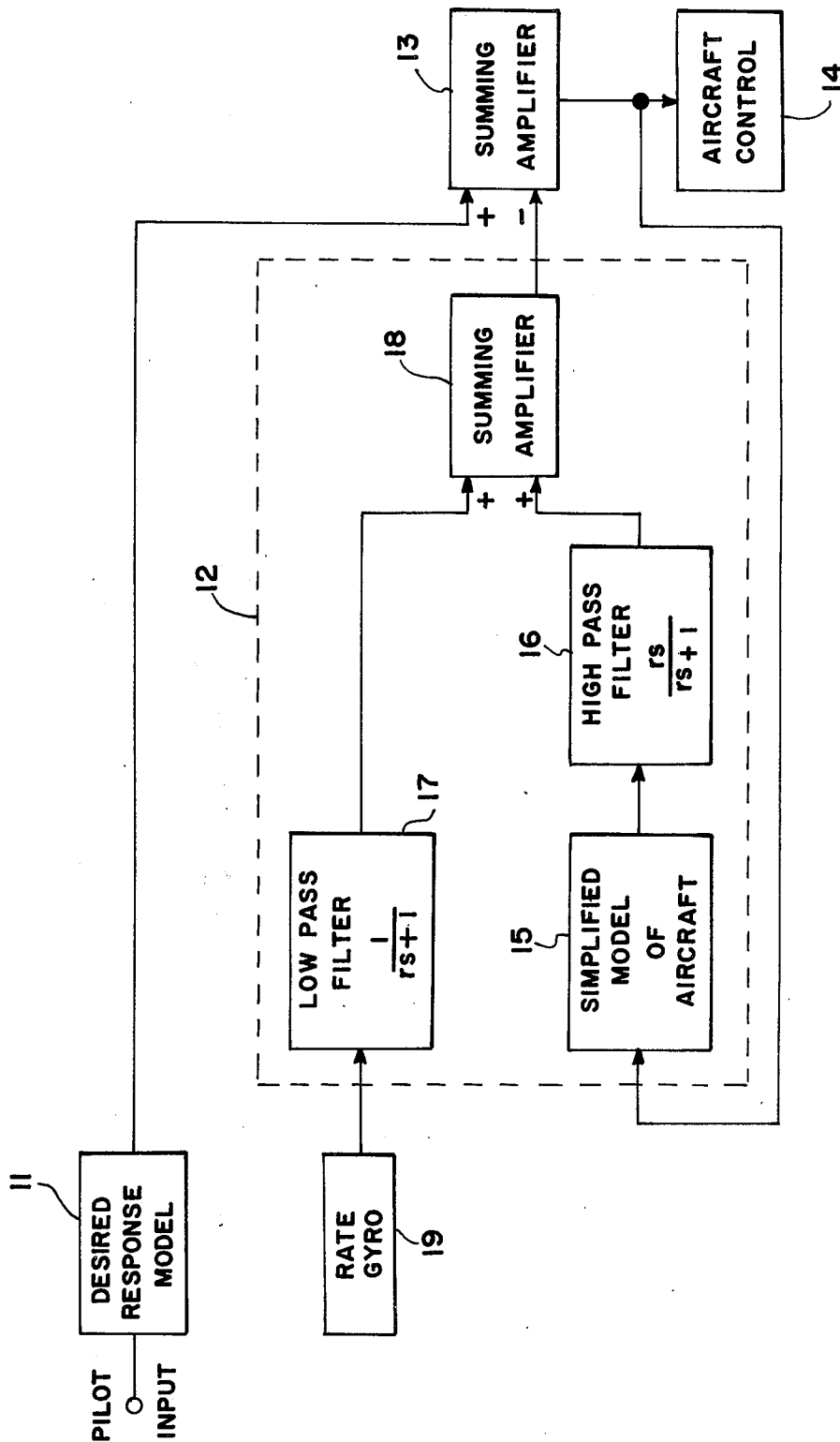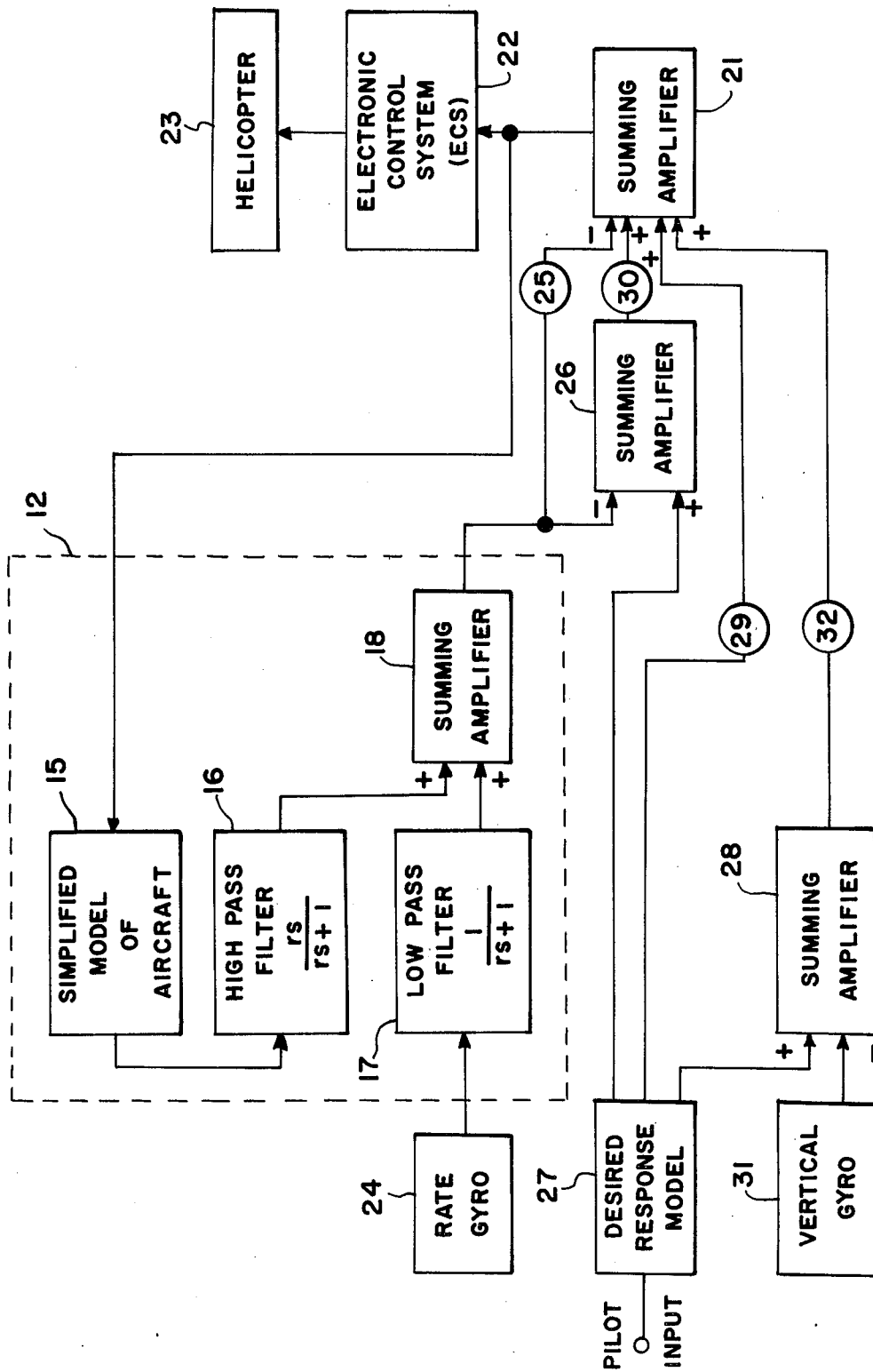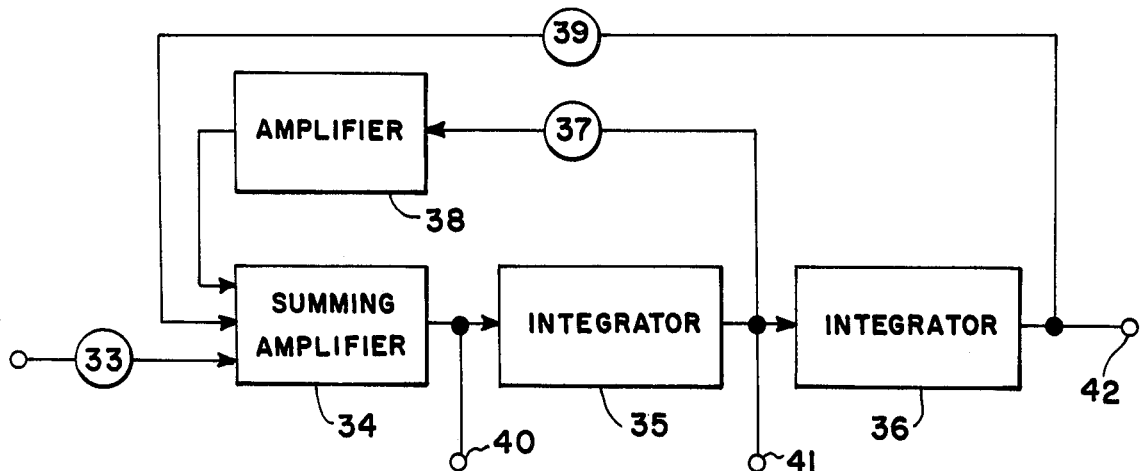
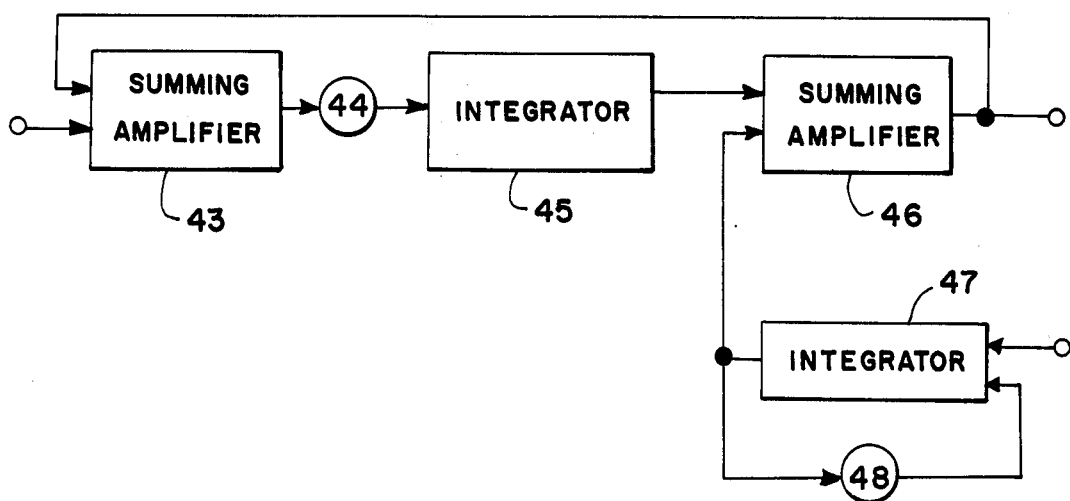**10 Claims, 4 Drawing Figures**

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FILTERING TECHNIQUE BASED ON HIGH-FREQUENCY PLANT MODELING FOR HIGH-GAIN CONTROL

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

The invention relates generally to aircraft control systems and more specifically the use of a complementary filtering technique to increase the frequency bandwidth of an aircraft control system in a high vibration environment.

Advanced control techniques for aircraft rely on the use of high-gain feedback from motion sensors to achieve improved performance in terms of disturbance rejection and response compliance. A direct measure of the degree of success that can be realized in achieving these benefits is the closed-loop frequency bandwidth, which is a function of the maximum feedback gain that can be achieved. In practice, the feedback gain level is limited by either noise amplification or control limit cycle, or by a combination of both.

In high vibratory environments such as helicopters experience, excessive noise amplification occurs even for modest gain levels. The noise encountered in helicopters is associated primarily with rotor-induced vibration and, therefore, contains harmonics of the rotational frequency. The frequency content corresponding to one cycle per rotor revolution and to n cycles per revolution, where n represents the number of blades per rotor, is usually the most bothersome from a control feedback standpoint because the amplitude is large and the frequency is so low that the control actuators and control surface aerodynamics can respond. Attempts to eliminate this low-frequency noise by classical filtering techniques introduces significant lag, which aggravates the limit-cycle problem, thereby requiring reduction in the feedback gain level. For feedback control applications where low gains can provide acceptable performance, such as in stability augmentation systems, classical filtering techniques are usually adequate. For the implementation of model-following and other control concepts requiring achievement of high-gain feedback, however, the situation has been less than satisfactory, with a severe operating compromise among noise, limit cycle, and performance.

It is therefore the primary object of this invention to increase the feedback gain that can be achieved in control techniques for aircraft.

Another object of this invention is to increase the feedback gain that can be achieved in model-following aircraft control techniques.

A further objective of this invention is to increase the resistance to external disturbances in aircraft control techniques.

Still another object of this invention is to use complementary filtering in aircraft control techniques to increase the control system frequency bandwidth due to simultaneous reduction in noise amplification and control limit-cycle tendencies.

Other objects and advantages of this invention will become apparent hereinafter in the specification and drawings.

SUMMARY OF THE INVENTION

The essential component of this invention is a complementary filter comprising a simplified model of the aircraft, a high-pass filter, a low-pass filter, and a summing amplifier. A signal proportional to control surface motion is fed to the simplified model of the aircraft which attempts to compute the aircraft response to the signal. This computed response is then fed to the high-pass filter to eliminate long-term errors in the computed response, with the result that a good estimate of the high frequency content of the aircraft motion is obtained. The output signal from a rate gyro attached to the aircraft is fed to the low-pass filter to eliminate all of the offending noise. The output of the low-pass filter which is a good estimate of the low frequency content of the motion is summed with the output of the high-pass filter by the summing amplifier. The time constants of the high-pass and low-pass filters are matched so that the sum of their outputs is an estimated angular rate signal. This estimated angular rate signal is then used as a motion feedback signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing the preferred embodiment of the invention used in a simple aircraft control system;

FIG. 2 is a block diagram showing the preferred embodiment of the invention in a more complex aircraft control system than that disclosed in FIG. 1;

FIG. 3 is a block diagram of the desired response model diclosed in FIG. 2; and

FIG. 4 is a block diagram of the complementary filter disclosed in FIGS. 1 and 2.

DETAILED DESCRIPTION OF THE DRAWINGS

Turning now to an embodiment of the invention selected for illustration in the drawings the number 11 in FIG. 1 designates a desired response model which produces the desired signal in response to the pilot's input. The pilot input is an electrical signal indicative of his actions to control the aircraft and can be derived from, for example, a potentiometer attached to the controls. The difference between this desired response signal and a signal from a complementary filter 12 is obtained by summing amplifier 13 to produce an error signal that is fed to an aircraft control 14 to control the motion of the aircraft. Complementary filter 12 comprises a simplified model of the aircraft 15, a high-pass filter 16, a low-pass filter 17 and a summing amplifier 18. The output signal from summing amplifier 13 is applied to simplified model 15 which attempts to compute the aircraft response to the signal. This computed response is then fed to high-pass filter 16 to eliminate long-term errors in the computed response, with the result that a good estimate of the high frequency content of the aircraft motion is obtained. In order to obtain a good estimate of the low frequency content of the motion, the output signal from a rate gyro 19 attached to the aircraft is fed through low-pass filter 17 which eliminates all of the offending noise from the signal. The time constants of the two filters are matched so that the sum of their outputs is a perfect angular rate signal. The output of summing amplifier 18 which is an estimated rate is then

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used as a feedback signal by subtracting it from the desired response signal from model **11** by means of summing amplifier **13**.

It is necessary that the time constants, r_1 and r_2, of filters **16** and **17** be identical in order to satisfy the requirement that the net effect of the two filters is an uncontaminated rate output. That this is true is demonstrated as follows: using the rule for summing transfer functions that are in parallel, the transfer function, F(s), that represents the combined effect of filters **16** and **17** becomes:

$$F(s) = \underbrace{\frac{r_1 s}{r_1 s + 1}}_{\text{Filter 16}} + \underbrace{\frac{1}{r_2 s + 1}}_{\text{Filter 17}}$$

If $r_1 = r_2$, the above equation becomes:

$$F(s) = r_1 s + 1 / r_1 s + 1 = 1$$

Hence, for this condition of identical values for r, the complementary filter acts as a unit transfer function insofar as the basic signal is concerned and contributes no dynamics to the system.

A simplified block diagram of the model following control system for which the complementary filter **12** was developed is shown in FIG. 2. Although similar systems can be used for the pitch and yaw degrees of freedom, only the roll degree of freedom system is shown in FIG. 2.

The control signal at the output of a summing amplifier **21** is applied through an electronic control system **22** to control a helicopter **23**. The control signal is also applied to the simplified model of the aircraft **15** which produces a signal proportional to the calculated roll rate. This calculated roll rate signal is passed through the high-pass filter **16** to summing amplifier **18**. The output signal from a rate gyro **24** which is proportional to the aircraft roll rate is passed through the low-pass filter **17** and then added to the calculated roll rate by summing amplifier **18**. The output signal from summing amplifier **18** which is proportional to the aircraft estimated roll rate, is applied to a summing amplifier **26** and through a potentiometer **25** to summing amplifier **21**. A desired response model **27** produces three output signals in response to the pilot's input. These three signals are proportional to the aircraft roll attitude, the aircraft roll rate and the aircraft roll acceleration. The aircraft roll attitude signal is applied to a summing amplifier **28**, the aircraft roll rate signal is applied to summing amplifier **26** and the aircraft roll acceleration signal is applied through a potentiometer **29** to summing amplifier **21**. The output of summing amplifier **26**, which is a signal proportional to the estimate roll rate error, is applied through a potentiometer **30** to summing amplifier **21**. The output from a vertical gyro **31**, which is a signal proportional to the aircraft roll attitude, is applied to summing amplifier **28**. The signal at the output of summing amplifier **28** is proportional to the actual roll attitude error and is applied through a potentiometer **32** to summing amplifier **21**.

A model suitable for use as the desired response model **27** in FIG. 2 is disclosed in FIG. 3. The pilot input is applied through a potentiometer **33** to a summing amplifier **34**. The output of the summing amplifier **34** is integrated by an integrator **35** the output of which is again integrated by an integrator **36**. The output from integrator **35** is applied through a potentiometer **37** and

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an amplifier **38** to summing amplifier **34**. The output from the integrator **36** is applied through a potentiometer **39** to summing amplifier **34**. The resulting output of integrator **36** is proportional to the aircraft commanded roll attitude which is connected at terminal **42** to summing amplifier **28** in FIG. 2. The output of integrator **35** is proportional to the aircraft commanded roll rate and is applied through terminal **41** to summing amplifier **26** in FIG. 2. The output of summing amplifier **34** is proportional to the aircraft commanded roll acceleration and is applied through terminal **40** to potentiometer **29** in FIG. 2.

A complementary filter suitable for use as filter **12** in FIGS. 1 and 2 is shown in FIG. 4. The output from the rate gyro is applied to a summing amplifier **43** the output of which is applied through a potentiometer **44** to an integrator **45**. The output of integrator **45** is applied through a summing amplifier **46** the output of which is connected back to the input of summing amplifier **43**. The control signal used to control the aircraft is applied to an integrator **47** which has a feedback potentiometer **48**. The output of integrator **47** is applied to summing amplifier **46** the output of which is the aircraft estimated roll rate.

The success of the complementary filter depends on being able to find a single value of r which is both large enough to reject noise on the gyro signal and yet small enough to reject, or washout, long-term errors in the calculated rate. Experience with classical filters in helicopters has shown that filter time constants which are large enough to attenuate noise adequately introduce so much phase lag that additional gains still cannot be achieved without reducing system stability and exciting limit cycle. The typical compromise between noise and limit cycle is usually the selection of a time constant on the order of 0.05 sec. Use of the complementary filter permits use of substantially larger time constant values, which improves noise rejection without encountering limit cycle.

The gains of the four signals summed by summing amplifier **21** are controlled by potentiometers **25**, **29**, **30** and **32**. The gain of the angular acceleration signal from the complementary filter is set by potentiometer **25** to prevent cancellation of the helicopter's inherent roll rate damping. The gain of the estimated roll rate error signal at the output of summing amplifier **26** is set by potentiometer **30** and is usually adjusted in flight to attain the maximum level that can be tolerated from the standpoint of control system noise or limit cycle; the higher the level of gain of potentiometer **30**, the better the closed loop system performance. The gain of the actual roll-rate error signal at the output of summing amplifier **28** is set by potentiometer **32** to be equal to the square of the gain of potentiometer **30** divided by four times the square of the desired damping ratio. The damping ratio, for example, can be equal to 0.7.

The advantages of this invention over the prior art is that the complementary filtering technique used provides an estimate of the desired motion parameter that is both free of noise and phase lag. This signal can be used, therefore, to drive the control system on a very high-gain without producing excessive control system noise or exciting control system instability.

What is claimed is:

1. In an aircraft control system in which the outputs from feedback devices including a feedback rate gyro are combined with the pilot input to produce a control

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signal for actuating the control surfaces of the aircraft, complementary filter means receiving said control signal and the output from said feedback rate gyro for producing an estimated angular rate signal that is free of both noise and phase lag and that is combined with said pilot input to produce said control signal.

2. In an aircraft control system as in claim **1** wherein said complementary filter means includes a simplified model of the aircraft receiving said control signal for producing a signal representing the aircraft's computed response to the control signal, a high-pass filter means receiving said computed response signal for eliminating long-term errors in the signal, a low-pass filter means receiving said output from said feedback rate gyro for eliminating the noise from the signal thereby giving a good estimate of the low frequency content of the motion of the aircraft, and means for summing the outputs of said high-pass and low-pass filters to produce said estimated angular rate signal.

3. In an aircraft control system as in claim **2** wherein the transfer functions of the high-pass filter and the low-pass filter are

(r_1s/r_1s+1) and $(1/r_2s+1)$, respectively, where r_1 and r_2 are the time constants for the two filters.

4. In an aircraft control system as in claim **3** wherein r_1 is equal to r_2.

5. In an aircraft control system as in claim **2** including means responsive to the pilot input into the controls of said aircraft for producing a desired rate response signal and means for subtracting said estimated rate signal from said desired rate response signal to produce said control signal.

6. In an aircraft control system as in claim **5** wherein said means for producing a desired rate response signal is a desired response model.

7. In an aircraft control system

means for summing signals to produce a control signal for controlling an aircraft roll rate signal and an aircraft roll acceleration signal in response to the input from the pilot of the aircraft;

a desired response model for producing signals proportional to aircraft roll attitude, aircraft roll rate and aircraft roll acceleration in response to the pilot input;

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a vertical gyro attached to the aircraft for producing an aircraft roll attitude signal;

means for obtaining the difference between the aircraft roll attitude signals produced by said desired response model and said vertical gyro and for applying a portion of the difference signal to said means for summing signals to produce a control signal;

a rate gyro attached to the aircraft for producing an aircraft roll rate signal;

a complementary filter means receiving said control signal and the output from said rate gyro for producing an aircraft estimated roll rate signal;

means for applying a portion of said estimated roll rate signal to said means for summing signals to produce a control signal;

means for obtaining the difference between said roll rate signal produced by said desired response model and said estimated roll rate signal to produce an estimated roll rate error signal; and

means for applying a portion of said estimated roll rate error signal to said means for summing signal to produce a control signal.

8. In an aircraft control system according to claim **7** wherein said complementary filter means comprises:

a simplified model of the aircraft receiving said control signal for producing a calculated roll rate signal;

a high-pass filter receiving said calculated roll rate signal for eliminating long-term errors in the signal;

a low-pass filter receiving the roll rate signal from the rate gyro for eliminating the noise from the signal thereby giving a good estimate of the low frequency content of the motion of the aircraft; and

means for summing the outputs of said high-pass and low-pass filters to produce said aircraft estimated roll rate signal.

9. In an aircraft control system according to claim **8** wherein the transfer functions of the high-pass filter and low-pass filter are

r_1s/r_1s+1 and $1/r_2s+1$, respectively,

where r_1 and r_2 are the time constants of the two filters.

10. In an aircraft control system according to claim **9** wherein r_1 is equal to r_2.

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